The Luminosity-Temperature Relation at z=0.4 for Clusters of galaxies

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ABSTRACT

We have obtained the first large sample of accurate temperatures for clusters at $z > 0.14$ from ASCA. We compare the luminosity temperature (L-T) distribution for these clusters with the low redshift sample of David et al (1993) and find that there is no evidence for evolution. We also find that the intrinsic variance in this relation is roughly constant with redshift. Additionally, there is no detectable change in the relationship of optical velocity dispersion to X-ray temperature with redshift. Most cosmological simulations driven primarily by gravity predict substantial changes in the L-T relation due to the recent rapid growth of clusters. Our results are consistent either with models in which the cluster core entropy is dominated by pre-heating, or with low Ω models in which cluster structure does not evolve strongly with time. The intrinsic variance in the L-T relation at a fixed redshift can be due a variety of possibilites e.g. a change in the baryonic fraction from cluster to cluster, variation in the fraction of the total energy in the system arising from shocks or supernova heating or variations in the emission measure distributions in multiphase gas.

Subject headings: galaxies:clusters:general - X-rays:galaxies - cosmology:observations

1. Introduction

Clusters of galaxies are the largest relaxed systems in the universe and as such provide a strong test of theories of the origin of and evolution of structure. A critical measurement (Frenk et al 1990) is the relationship of the mass of a system to its temperature. This can be best probed by comparing the evolution of the X-ray luminosity (which is related to the baryonic mass) to the x-ray temperature, which is roughly proportional to $M^{2/3}$. Calculations of the evolution of these quantities (c.f., Kang et al 1994, Kaiser 1991) indicate that, in a closed universe, where gravity dominates the evolution of the gas and the dark matter, the relationship between luminosity and temperature should evolve strongly at all redshifts, with significant changes occurring at $z < 0.5$. However the nature and amplitude of the evolution is dependent on the details of the cosmological model (Bryan et al 1994).

For example, evolution is less in the CDM+ Λ=1 model than in a pure CDM universe and is also less in a low density universe, or one in which the entropy of the gas is relatively large at high redshift (Kaiser 1991, Bower 1997, Navarro, Frenk and White 1995). This evolution is not necessarily monotonic. Cen & Ostriker (1994) show that in a CDM+Λ=1 model there is an almost constant mean cluster temperature from $z \sim 0.3$ to the present while in a CDM model there is a sharp decrease in the temperature from $z = 0.0$ to $z = 0.3$.

At low redshift the L-T relation is well measured (Mushotzky 1984, Edge & Stewart 1991, David et al 1993). While the correlation is good, there is a fair degree of scatter (Fabian et al 1994), with cooling flow clusters being rather more luminous for a given temperature. The theoretical prediction for the relationship between luminosity and temperature in a CDM universe dominated by gravity (Frenk et al 1990, Kang et al 1994, Evrard 1990) is somewhat flatter than observed. There are various possible explanations for this such as systematic variations in the baryonic fraction with cluster mass (David et al 1993) or pre-heating (Evrard 1990).

At low redshifts the relationship between the cluster velocity dispersion (σ_V)and the gas temperature (Bird, Mushotzky & Metzler 1995, Bachall & Lubin 1994, Girardi et al 1996) is very tight, consistent with both tracing the same potential. This strong agreement is not generally predicted to continue at higher redshift.

ASCA data allow, for the first time, a measurement of the L-T and the σ_V-T relationships at $z \gtrsim 0.1$ from a large sample of clusters. Thereby placing strong constraints on theories of cluster evolution. In this paper we use a sample of 38 clusters of galaxies from $z \sim 0.14 - 0.55$ obtained from the ASCA archives. This sample, while not homogeneously chosen, is large enough to constrain this relationship at $\langle z \rangle \sim 0.3$.

The only previous attempt to measure the L-T relationship at $z \gtrsim 0.1$ (Henry, Jiao & Gioia 1994) was consistent with no evolution, but with rather large errors. However, this study relied on summing a large number of low signal to noise data sets from the flux limited Einstein medium survey and was therefore fundamentally different in character. The ASCA data have well determined temperatures for each cluster but are drawn from a heterogeneous sample.

2. Observations

We have extracted the spectra from 38 clusters of galaxies at $z > 0.14$ from the ASCA archive (Table 1). The sample simply consists of all clusters available before Nov. 1996 for which the data are publicly available, the temperature uncertainty is $\delta T/T \lesssim 0.3$, and there is no strong substructure visible in the ASCA image. In our analysis we allowed the cluster abundance and galactic absorption to be free parameters. For clusters at $z \sim 0.3$ this effectively requires cluster flux $\times \sim 4 \times 10^{-8}$ ergs cm^{-2}.

Examination of the data (Figure 1) shows a relatively strong selection bias against

clusters of $L_{bol} < 10^{45}$erg s^{-1} at $z \sim 0.3$. This comes from the desire of many of the proposers to obtain higher quality spectra, requiring bright sources and/or longer exposures than normal with ASCA, combined with the relatively small number of known clusters in this luminosity/redshift range.

At $z \sim 0.3$ clusters of $L_{bol} < 10^{45}$ are below the threshold of the ROSAT all sky survey and mainly come from the EMSS data base (Gioia et al 1990) and serendipitous ROSAT sources. At flux levels $\gtrsim 10^{-12}$erg s^{-1}cm^{-2} the ASCA data analysis is relatively straightforward (see Mushotzky & Loewenstein 1997 for a discussion of the higher signal to noise objects in this sample). We have used the latest calibrations including the gain change in the SIS detectors.

Quoted errors are 90% confidence for one parameter (χ^2+2.71). We use $q_0 = 0$ and $H_0 = 50$ km s^{-1} Mpc^{-1} in this paper. Our derived temperatures agree very well with those obtained by Tsuru 1996, for common objects and the previously published results of Schindler et al 1997, Allen et al 1996, Bautz et al 1994 and Donahue 1996.

We have integrated the spectra over 3-6 arcmin in radius, depending on cluster redshift, in an attempt to get the average spectrum in a fashion similar to those obtained by non-imaging proportional counters for lower redshift objects. Thus our values are directly comparable to those of the non-imaging experiments. The effects of cooling flows (Allen et al 1996), mergers (Henriksen & Markevitch 1996) or non-isothermal profiles (Markevitch 1996) can change the mean temperature by up to ±20%. For example, in A1835 which has a very large cooling flow, the mean kT=8.15 keV (Table 1 and Allen, Fabian & Kneib 1996) changes to 9.5 keV with the inclusion of a cooling flow in the spectral fit. The uncertainties in the temperature for these high z systems are similar to or less than the errors obtained from EXOSAT (Edge & Stewart 1991), HEAO-1 (Mushotzky 1984) or the Einstein MPC (David et al 1993) proportional counters, and thus form a good comparison

sample. We have added a few low z clusters to the David et al (1993) compilation (A3158 and A3581) and obtained accurate ASCA temperatures from our own analysis and the literature for those low z clusters with large temperature uncertainties in the David et al (1993) compilation (A399, A401, A3112 and A3391) to obtain an essentially flux limited low z sample resulting in a total sample of 102 clusters from $z \sim 0.01$ to $z \sim 0.55$.

3. Analysis

Comparison of this sample ($z > 0.14$) with the enhanced David et al (1993) sample of low redshift clusters ($z < 0.1$) shows no evidence for a change in the L-T relationship (Figure 1) over the whole luminosity range covered ($\log_{10} L_{bol} > 44.3$). However the ASCA data show a strong bias at the low luminosity end of the distribution due to the absence of objects in the database. We believe this selection effect accounts for the apparent flattening of the L-T relationship for the high z clusters at low luminosities (Figure 1). Thus we restrict our analysis to $45.2 \leq \log_{10} L_{bol} \leq 45.7$ for which there are no strong selection effects and for which there is maximum overlap of the low and high z data sets and a reasonable set of objects (39). Applying the two dimensional Kolmogorov-Smirnov test we find that at $45.2 \leq \log_{10} L_{bol} \leq 45.7$ the low and high z data show no evidence of being significantly different (probability of being different < 60% for all high/low redshift divisions). The inclusion of the lowest luminosity points, combined with a smaller data set led Tsuru et al (1994) to infer a change in the L-T relation which is not seen in the present data.

The high z, large accretion rate, cooling flow clusters in Figure 1 (e.g. RXJ1347, A1835, EMSS1455 occupy a ridge line to the right in the L-T plot. This property was noted in the low z sample by Fabian et al (1994).

We estimate the allowed change in either the normalization or slope of this relation

by examining the variation in the mean temperature in redshift shells. In Figure 2 the mean cluster temperatures determined by maximum likelihood are plotted as a function of redshift bin. Much of the plotted allowed range in the mean temperature is not due to uncertainties in the data but to real width in the L-T relation, as seen in the low z sample (Figure 1 and Fabian et al 1994). Solid vertical error bars represent the 90% confidence limits on $\langle T \rangle$, dotted error bars indicate the intrinsic dispersion of the L_{bol}-T distribution estimated by likelihood analysis. Using $q_0 = 0.5$ gives a small but significant change in the normalization, such that higher redshift clusters are less luminous for a given temperature.

The limits on temperature evolution are estimated from Figure 2 as: $\Delta \log_{10} \langle T \rangle \simeq 0.04$ for $\Delta \log_{10}(1 + z) \simeq 0.15$ at fixed luminosity.

We also compare the relationship of velocity dispersion to temperature and luminosity, using the large sample of Fadda et al (1996) for the low z sample and the Carlberg et al (1996) and Fabbricant et al (1991) data for the high z sample. We find that the high z clusters in the temperature range 4-9 keV show virtually identical σ_V-T and σ_V-L relationships to those of the low z sample (Figure 3). AC118 and A1689 are clearly discrepant, indicating non-virial velocity dispersion.

4. Discussion

The lack of evolution in the L-T relation at $z < 0.5$ combined with the recent upper limits on the evolution of the luminosity function over the same redshift range places strong constraints on all models of cluster evolution (Kaiser 1991). As pointed out in detail by Navarro, Frenk and White (1995) a model in which the intial specific entropy is large results in little, if any, evolution in the L-T plane and better matches the overall slope of the observed L-T relation. Metzler and Evrard (1994) describe a model in which entropy

due to the creation of the metals is explicitly included, increasing the overall entropy of a kT$\sim$ 6 keV cluster by a factor of 2 and producing a value of the entropy that agrees well with that of several nearby clusters. This result is sensitive to the thermalization of the supernova shock energy. However, as David et al (1996) point out, the central entropy does vary from cluster to cluster, in agreement with the scatter in the L-T plot.

Bower (1997) has parameterized the evolution of cluster central gas entropy as a power of the expansion factor: $s_{min} = s_{min}(z = 0) + c_v \epsilon ln(1 + z)$ (c_v is specific heat capacity of the gas at constant volume). In this case $\epsilon = 0$ corresponds to constant entropy. Data on the evolution of the cluster XLF and L-T relationships can then be used to constrain two parameters; ϵ and n, the power spectrum index of matter density fluctuations (Bower 1997). Our results imply that over the redshift range $0 < z < 0.4$, $\epsilon = 0 \pm 0.9$. If the evolution of the ICM followed that of the dark matter (e.g. Kaiser 1986) then our limits on ϵ would imply $n > 2$ always, thereby firmly ruling out self-similar evolution of clusters. If there is little or no evolution in the XLF (e.g. Ebeling et al 1997) then our result implies that $-1.5 \lesssim n \lesssim -0.5$. Recent measurements of the low luminosity cluster population at high redshift (Jones et al 1997) are also consistent with zero evolution in the XLF.

Bryan (1996) presents a scaling relation between L$_{bol}$ and T with a $(1+z)^{3/2}$ dependence for $\Omega = 1$. The dashed curve in Figure 2 represents this scaling, normalised to the luminosity band used here. Clearly the Bryan model cannot be rejected, although it does not appear to describe the data particularly well. The same statement can be made about the results of Kitayama and Suto (1996) who have improved on Press-Schechter theory by including the epoch of cluster formation, and predict a similar (negative) temperature evolution.

The lack of evolution in the σ_V-T relation also indicates that the gas and the galaxies are sampling the same potential (c.f. Carlberg et al 1996) and that both change in the same way with redshift, a result not generally expected in many models.

Presumably a similar lack of evolution would be seen in low density universe models in which cluster evolution occurs early and structure stops forming at $z \sim \Omega^{-1}$. However, detailed calculations for such models are not yet available.

5. Conclusion

We find no evolution in the cluster L-T relation as a function of redshift. These results are consistent with models in which the cluster core acquired a high initial entropy (Navarro, Frenk and White 1995) as required by the recent determination of the origin of the cluster metals (Mushotzky et al 1996) and the lack of evolution in the cluster metallicity (Mushotzky & Loewenstein 1997). However, it is likely that this result is also consistent with low density cosmologies in which clusters stop evolving at relatively high redshifts, or other variants of the standard models. We hope that this large data set will enourage detailed theoretical modeling.

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REFERENCES

Allen, S., Fabian, A., Kneib, J., P. 1996, MNRAS, 279, 615

Allen, S. Fabian A., Edge, A., Bautz, M., Furuzawa, A. and Tawara, Y., 1996, MNRAS, 283,263

Bachall, N. and Lubin, L., 1994 ApJ, 426, 513

Bautz, M. et al, 1994, PASJ, 46, L131

Bird, C., Mushotzky, R. and Metzler, C., 1995, ApJ, 453,40

Bower, R. G., 1997, preprint astro-ph/9701014

Bryan, G., Cen, R., Norman, M., Ostriker, J. and Stone, J., 1994, ApJ, 428, 405

Bryan, G., 1996, PhD Thesis Univ. of Illinois

Carlberg, R., Yee, H., Ellingson, Abraham, R., Gravel, P., Morris, S. and Pritchet, C., 1996, ApJ, 462, 32

Cen, R., Ostriker, J., P., 1994, ApJ, 429, 4

David, L., Slyz, A., Jones, C., Forman, W. Vrtilek, S. and Arnuad, K., 1993, ApJ, 412, 479

David, L., Jones, C., and Forman, W., 1996, ApJ, 473, 692

Donahue, M., 1996, ApJ, 468,79

Ebeling, H., Edge, A., Fabian, A., C., Allen, S. Crawford, C. and Boehringer, H., 1997, ApJ, in press

Ebeling, H., Voges, W., Bohringer, H., Edge, A. C., Huchra, J. P., Briel, U. G. 1996, MNRAS, 281, 799

Edge, A. and Stewart, G., 1991, MNRAS, 252, 428

Evrard, A., 1990, ApJ, 363, 349

Evrard, A. and Henry, J., P., 1991, ApJ, 383, 95

Fabian, A., C., Crawford, C., Edge, A. and Mushotzky, R., 1994, MNRAS, 267, 779

Fabricant, D., McClintock, J., and Bautz, M., 1991, ApJ, 381, 33

Fadda, D. Girardi, M., Giuricin, G., Mardirossian, F. and Mezzetti, M. 1996, ApJ, 473, 670

Frenk, C., White, S., D., M., Efstathiou, G. and Davis, M. 1990 ApJ, 351, 10

Gioia, I., Henry, J., P., Maccacaro, T., Morris, S., Stocke, J. and Wolter, A. 1990, ApJS, 72, 567

Girardi, M., Fadda, D., Giuricin, G., Mardirossian, F., Mezzetti, M. and Biviano, A. 1996, ApJ, 457, 61

Henriksen, M. and Markevitch, M. 1996, ApJ, 466, L79

Henry, P., Jiao, L. and Gioia, I. 1994, ApJ, 432, 49

Jones, L., R., Scharf, C. A., Perlman, E., Ebeling, H., Wegner, G. and Malkan, M. 1997 preprint

Kaiser, N. 1986, MNRAS, 262, 627

Kaiser, N. 1991, ApJ, 383, 104

Kang, H. Cen, R. Ostriker, J., P. and Ryu, D. 1994, ApJ428, 1

Loewenstein, M. and Mushotzky, R. 1996, ApJ, 465, 695

Markevitch, M. 1996, ApJ, 465, 1

Markevitch, M., Mushotzky, R., Inoue, H., Yamashita, K., Furuzawa, A., Tawara, Y. 1996, ApJ, 456, 437

Matsuura, M. et al. 1996, ApJ, 466, L75

Metzler, C. and Evrard, G. 1994, ApJ, 437, 564

Mushotzky, R. 1984 Physica Scripta Vol T7, 157

Mushotzky, R. and Loewenstein, M. 1997, ApJ, submitted

Mushotzky, R., Loewenstein, M., Arnaud, K., Tamura, T., Fukazawa, Y., Matsushita, K. Kikuchi, K. and Hatsukade, I. 1996, ApJ, 466, 686

Navarro, J., Frenk, C. and White, S.,D.,M. 1995, MNRAS, 275, 720

Schindler, S., Hattori, M., Neumann, D. and Bohringer, H. 1996, Astron. & Astrophys., submitted

Tanaka, Y., Inoue, H. and Holt, S., S. 1994, PASJ

Tsuru, T., Koyama, K. Hughes, J., Arimoto, N., Kii, T. and Hattori, M. 1996 page 375 in UV and X-ray Spectroscopy of Astrophysical and Laboratory Plasmas edited by K. Yamashita and T. Watanabe Universal Academy Press Tokyo Japan

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Fig. 1.— X-ray luminosity vs gas temperature for low redshift ($z < 0.1$) (open squares) and high redshift ($z > 0.14$) (dark triangles) clusters. The errors in the gas temperature are symmetrized 90% confidence errors. The dashed and solid lines are unweighted linear regression fits to the high and low z data respectively.

Fig. 2.— The mean cluster temperature (in the luminosity band $45.2 \leq \log_{10} L_{bol} \leq 45.7$) estimated by maximum likelihood is plotted versus redshift. Redshift bins contain 6 objects, the highest z bin at $z \simeq 0.45$ contains 3 objects. Solid, vertical, errorbars show the 90% confidence limits on the mean, horizontal errorbars show size of redshift bin. Dotted, vertical, errorbars show the intrinsic variance in T, estimated by maximum likelihood. The dashed curve is the Bryan (1996) model prediction normalized to this luminosity band.

Fig. 3.— The optical velocity dispersion vs X-ray temperature. The errors in temperature are as in Figure 1 while the errors in the velocity dispersion are symmetrized 68% confidence errors. We have labelled A1689 and AC118 as being obvious outliers of the distribution function. The line drawn assumed that kT=σ_V^2 and is not a fit to the data

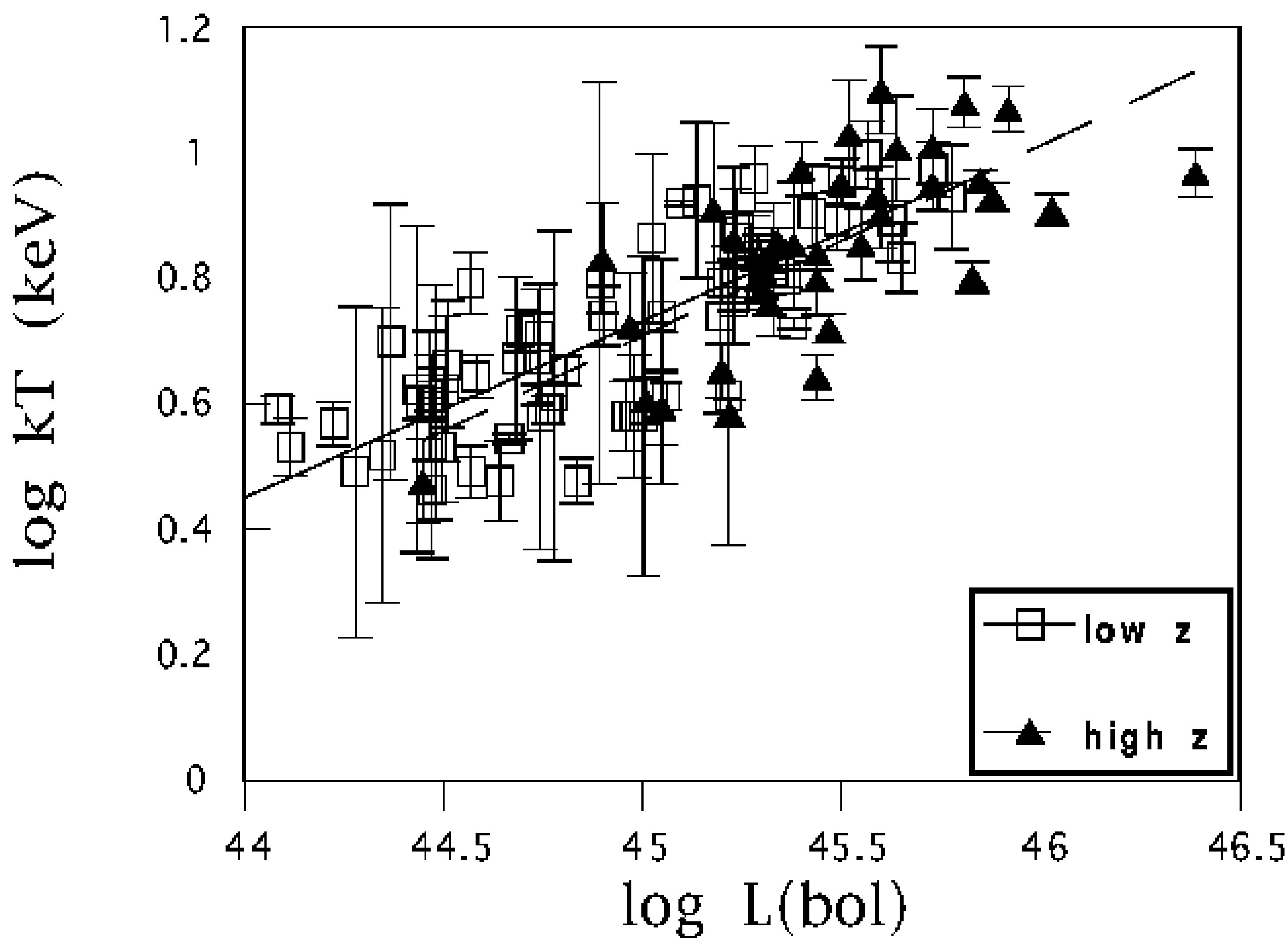
Name	Redshift	$\log_{10} L_{bol}$	kT (keV)
A1413	0.1430	45.440	$6.72(^{6.98}_{6.46})$
A2204	0.1530	45.880	$8.47(^{8.901}_{8.05})$
A1204	0.1700	45.220	$3.83(^{4.02}_{3.64})$
A2163 [a]	0.2010	45.600	$12.7(^{14.7}_{10.7})$
A2218	0.1710	45.340	$7.04(^{8.01}_{7.07})$
A586	0.1710	45.280	$6.61(^{7.76}_{5.65})$
A1689	0.1800	45.850	$9.02(^{9.42}_{8.72})$
A1246	0.1870	45.290	$6.28(^{6.82}_{5.79})$
MS0440	0.1900	44.970	$5.3(^{6.57}_{4.45})$
MS0839	0.1940	45.010	$4.19(^{4.55}_{3.86})$
A520	0.2010	45.590	$8.59(^{9.52}_{7.69})$
A963	0.2060	45.320	$6.76(^{7.20}_{6.27})$
A773	0.1970	45.500	$9.66(^{10.69}_{8.76})$
A1704	0.2190	45.200	$4.51(^{5.07}_{4.17})$
A1763	0.1870	45.550	$8.98(^{10.00}_{8.14})$
A2219	0.2280	45.920	$11.77(^{13.03}_{11.03})$
A2390	0.2300	45.730	$8.9(^{9.87}_{8.13})$
MS1305+29	0.2410	44.450	$2.98(^{3.50}_{2.57})$
A1835	0.2520	46.030	$8.15(^{8.61}_{7.70})$
MS1455	0.2580	45.480	$5.45(^{5.74}_{5.17})$
A1758N	0.2800	45.640	$10.19(^{12.48}_{8.5})$
A483	0.2830	44.900	$6.87(^{8.46}_{5.66})$

[a] Markevitch et al 1996

ZW3146	0.2900	45.830	$6.35(^{6.72}_{6.01})$
MS1008-12	0.3010	45.230	$7.29(^{9.74}_{5.77})$
A1722	0.3270	45.320	$5.87(^{6.38}_{5.46})$
AC118	0.3080	45.810	$12.08(^{13.5}_{11.2})$
MS2137	0.3130	45.440	$4.37(^{4.75}_{4.03})$
A1995	0.3180	45.520	$10.70(^{13.2}_{8.9})$
MS0353-36	0.3200	45.270	$8.13(^{10.7}_{6.4})$
MS1358	0.3270	45.280	$6.50(^{7.18}_{5.86})$
A959	0.3530	45.440	$6.95(^{8.80}_{5.62})$
A370	0.3730	45.550	$7.13(^{8.18}_{6.30})$
MS1512+36	0.3720	45.050	$3.57(^{4.90}_{2.83})$
A851	0.4100	45.180	$6.7(^{9.4}_{5.0})$
RXJ1347-114	0.4510	46.390	$11.37(^{12.47}_{10.45})$
3C295	0.4600	45.380	$7.13(^{9.19}_{5.78})$
MS0451-03	0.5390	45.730	$10.17(^{11.72}_{8.91})$
CL0016 [b]	0.5410	45.600	$8.0(^{9.00}_{7.0})$

[b]Furuzawa et al 1997, ApJ submitted

Note. — Numbers in brackets in final column correspond to the 90% confidence limits on the temperatures. An inspection of other works (e.g. David et al 1993, Ebeling et al 1996) indicates a scatter of $\lesssim 20\%$ in quoted L_{bol} which we attribute to differences in techniques.


log kT (keV)
log L(bol)
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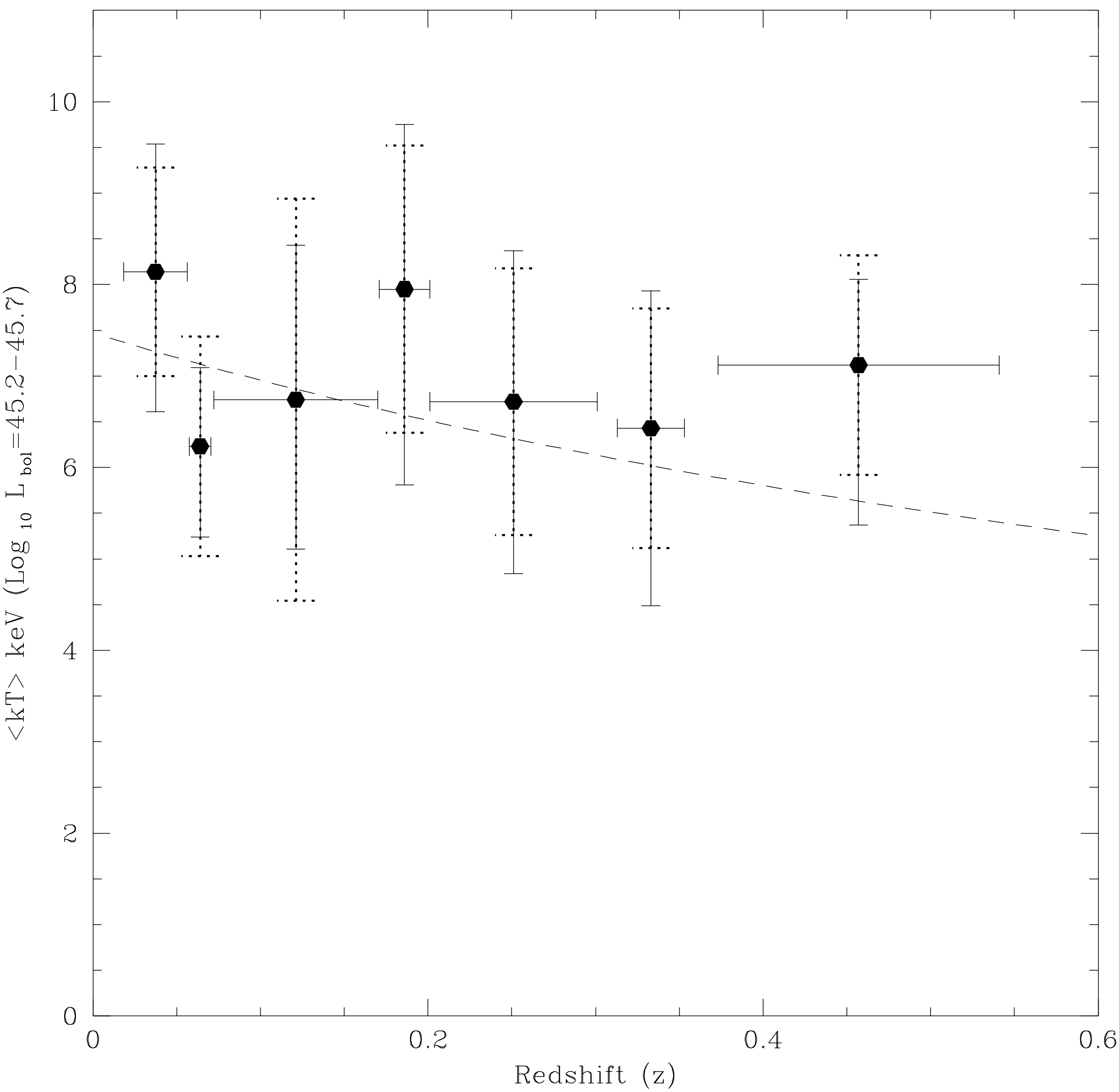
0.6
0.4
0.2
0
44
44.5
45
45.5
46
46.5
low z
high z



<kT> keV (Log 10 L bol=45.2−45.7)
Redshift (z)
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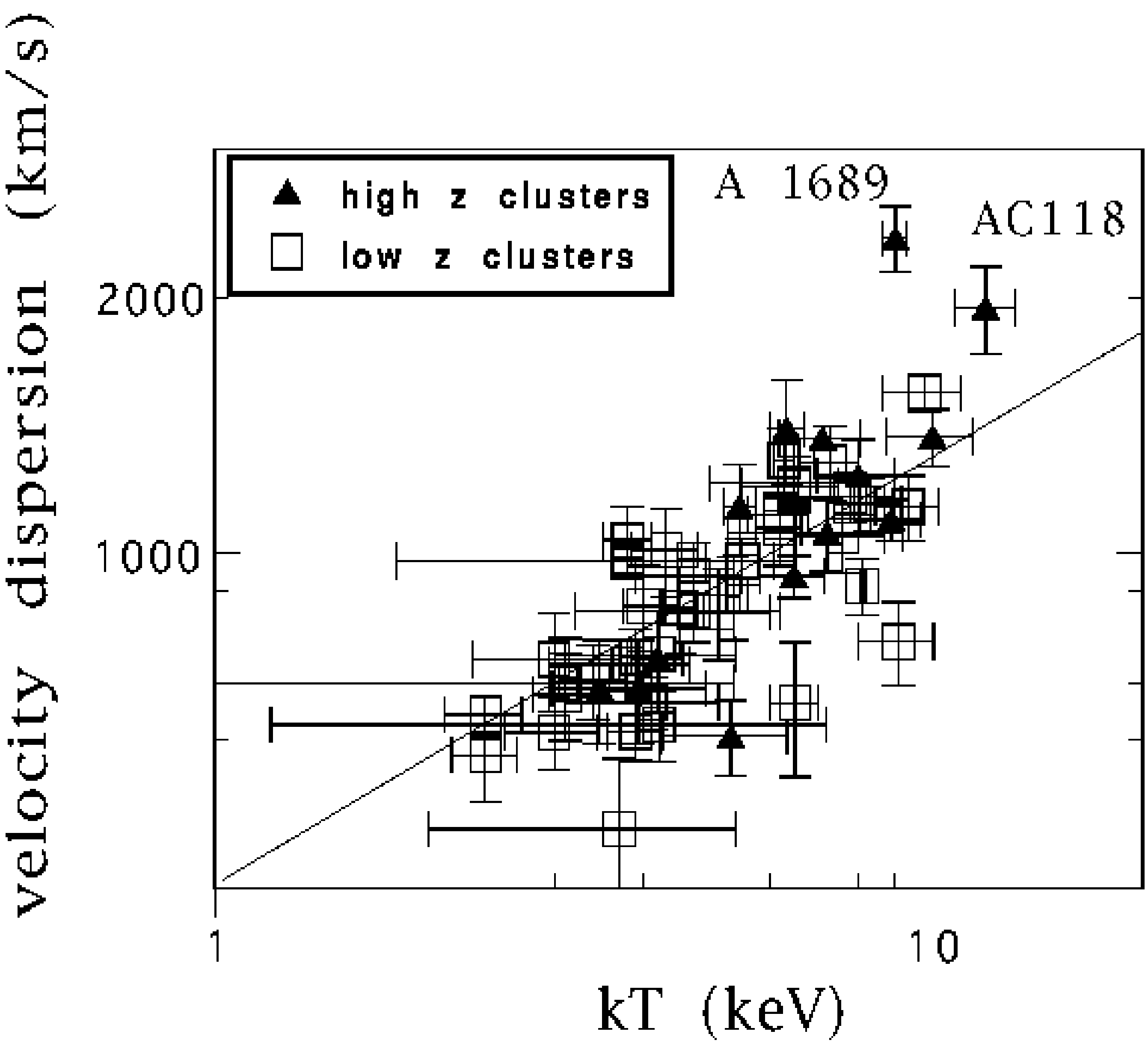
4
6
8
10
0
0.2
0.4
0.6



velocity dispersion (km/s)
2000
1000
1
10
kT (keV)
high z clusters
low z clusters
A 1689
AC118